Tectonic evolution of the Tertiary basin at Batu Arang, Selangor Darul Ehsan, Peninsular Malaysia

J.K. RAJ

Department of Geology
University of Malaya
50603 Kuala Lumpur

Abstract: In the Batu Arang area are found Tertiary sedimentary rocks that outcrop within an approximately elliptical basin surrounded by undulating to hilly terrain developed over Permian meta-sedimentary rocks consisting of quartzites, schistose quartzites, phyllites, indurated shales and rare cherts. The Tertiary strata cover an area of some 15 km² and rest unconformably over the meta-sedimentary rocks that generally strike NNW-SSE with variable, steep to vertical dips.

The Tertiary strata can be separated into two sequences: an upper one termed the Boulder Beds that consists of semi-consolidated, sandy to gravelly and bouldery sediments that unconformably overlie the lower sequence known as the Coal Measures or Batu Arang Beds comprising interbedded shales, structureless clays, fine grained to pebbly sandstones and some lignite seams.

The Boulder Beds consist mainly of sub-angular to rounded, pebble to boulder sized clasts of quartzite, sandstone and vein quartz as well as minor chert, schist, phyllite and shale fragments, in a matrix of gravel, sand or clayey sand, though a few beds of inter-stratified sand and sandy clay are also seen. Differences in colour, as well as differences in composition and roundness of clasts, has allowed for differentiation of three separate sequences within the Boulder Beds. The Beds are up to 300 m thick at the centre of the basin where their bedding is horizontal, though along the basin edges, they show inward dips of 20° to 45°. A number of small, syn-depositional, normal faults, and post-depositional, wrench faults, cut these beds whose age is not know, though a late Middle Miocene to Pliocene age is proposed by correlation with regional tectonic events. The Boulder Beds are alluvial fan deposits that have developed through erosion of steep, fault induced slopes.

The Coal Measures or Batu Arang Beds consist of several facies arranged in the following stratigraphical order: i) Sandstone with shale and clay intercalations, ii) Shale, iii) Coal beds, comprising two main coal seams, shale and sandstone, and iv) Sandstone with shale and clay and minor conglomerates including a basal pebbly sandstone. The strata show a synclinal structure plunging gently southeastwards, with the strata having an average dip of 14° towards the centre of the basin, though local variations are common especially towards the basin edges. The fine grained sediments range from stiff, structureless clays to well laminated and fissile shales containing abundant carbonaceous material. The shales are also often silty and even sandy and grade into clayey sandstone in places. The inter-bedded sandstones are mostly fine grained, though ranging up to coarse grained, and even pebbly. The coal occurs mostly as thin laminae or streaks in shales, but also builds thicker layers of more than 30 cm thick. In the eastern part of the basin, two thick coal seams are found as well as some thin beds of coal and coaly shale. The two seams are about 65 m stratigraphically apart; the Upper Seam attaining a thickness of up to 15 m, and the Lower Seam averaging 8 m in thickness. The coal appears to be intermediate between high-grade lignite and sub-bituminous coal and is a hard, black rock with a resinous lustre. Palynomorph assemblages indicate an Eocene to Oligocene age for the coals that are likely to have been peat-swamp deposits in an alluvial plain setting, whilst the inter-bedded shales were deposited in a freshwater lacustrine setting.

Correlation with known stratigraphic successions in Sumatra shows that the Coal Measures are time-equivalent (Late Eocene-Early Oligocene) with, and have a somewhat similar depositional history as, the Parapat Formation of the North Sumatra Basin, the Permatang Group and Kelesa Formation of the Central Sumatra Basin, and the Lahat Formation of the South Sumatra Basin. Differences in lithology, however, occur and reflect differences in geographical locations; the sediments at Batu Arang having been deposited at a higher altitude, and in a more inland location, as compared with the Sumatran Basins that formed at lower altitudes, close to the then Sundaland coastline. Differences in geographical locations have also influenced the subsequent geological histories of the individual basins.

No lithological equivalent of the Boulder Beds is found in the Tertiary strata of the Sumatran Basins, though its deposition is considered to be time-equivalent (Middle Miocene-Pliocene) with the Baong Formation of the North Sumatra Basin, the Minas Group and Binio Formation of the Central Sumatra Basin, and the Air Benakat Formation of the South Sumatra Basin.

Correlation with regional tectonic events indicates that a pull-apart basin (of half-graben shape)

developed at Batu Arang during the Late Eocene to Early Oligocene as a result of sinistral displacements along two pre-existing, NW-SE trending faults. The tectonic setting required for this event is considered to be the east-west orientated maximum horizontal component of the regional stress field that developed when the Indian Plate collided with the Eurasian Plate. Deposition in a swampy, alluvial flood-plain to lacustrine environment within the basin, then led to the strata now represented by the Coal Measures (or Batu Arang Beds). Continued northward movement of the Indian Plate led to a progressive clockwise rotation of Peninsular Malaysia, and of the regional stress field, and resulted in mild folding and uplift of the Coal Measures during the late Early Oligocene. During the late Middle Miocene, concomitant with, or following, uplift of the Barisan Mountain Range in Sumatra, there developed an extensional tectonic setting at Batu Arang which led to uplift of the surrounding areas, and the creation of steep scarps, particularly along the pre-existing, NE-SW trending fault boundaries. Rapid erosion of the scarps then led to deposition of the Boulder Beds in a subsiding basin with syn-depositional faulting during the Late Miocene to Pliocene. A compressional tectonic setting during the Pliocene, associated with rifting in the Andaman Sea, then led to minor wrench faulting and possibly warping of all the strata at Batu Arang. During the Late Pliocene and Quaternary, there has been isostatic uplift of the Tertiary strata with subsequent erosion and development of the present-day topography.

From the inferred tectonic evolution of the Tertiary basin at Batu Arang, it is considered likely that some inland areas of the Peninsula with Quaternary deposits, such as Rawang, Ulu Kanching, Kundang and Kuala Lumpur, were also initially formed as early as the Late Eocene to Early Oligocene, though their underlying carbonate bedrock modified their subsequent geological histories. These areas, whose southern and northern boundaries are often defined by NW-SE trending faults, are also considered to have experienced subsidence concomitantly with deposition of the Boulder Beds during the late Middle Miocene to Pliocene. Boulder Beds, mapped underneath Quaternary deposits in some of the areas, as at Ulu Kanching, may therefore be of a similar age. In view of its geological setting, and location within a zone of subsidence demarcated by NW-SE trending faults, it is here postulated that there are likely to be Tertiary strata underlying the Quaternary sediments in the Sungai Buloh area.

INTRODUCTION

The known Tertiary sediments of Peninsular Malaysia mainly occur on its West Coast in a series of small basins lying between the Strait of Malacca and the mountains of the interior (Fig. 1). All these basins are low-lying, being barely above the level of the alluvial plains, and are very poorly exposed, except where mining operations have been carried out. The sediments comprise partly consolidated gravels and sands, soft, often carbonaceous shales, seams of low-grade coal (lignite), and rare calcareous shale, tuff and limestone. The sediments, which are up to a few hundred metres thick, are mainly, and probably entirely, continental, lacustrine, paludal, and fluvial deposits (Stauffer, 1973). They are generally almost flat-lying, though dips of 30° to 40° occur, and a synclinal or basinal structure demonstrated for some of them. All the Tertiary occurrences also lie unconformably on much older, Palaeozoic to early Mesozoic rocks that are generally folded and partly metamorphosed (Renwick and Rishworth, 1966).

The most intensely studied and best known of the Tertiary deposits is at Batu Arang in Selangor Darul Ehsan where coal was first reported in 1908. Subsequent prospecting by the Mines Department between 1909 and 1910, involving the sinking of several pits as well as the use of a hand boring set, and the driving of an adit, proved the existence of a coal seam some 15.3 m thick that dipped about 15° and extended along strike for more than 800 m.

A second coal seam, some 7.3 m thick, underlain by sandy ground, was also identified to be present below the large seam exposed in the adit. Continued prospecting by diamond drilling, hand-boring and pitting during 1912 proved further extension of the coal-bearing strata to a radius of 4.8 km from the adit (Renwick and Rishworth, 1966).

Coal mining was started in 1915 and continued till 1960 with both surface and underground methods; the choice of method being influenced by demand and the limitations posed by a thick overburden (Mackie, 1938; Roe, 1940; Powell Duffryn, 1954). The coal was mined from two main seams; the Upper Seam (some 15 m thick) and the Lower Seam (about 8 m thick) which is some 65 m stratigraphically below the Upper Seam. Where the coal seams outcropped at the surface, they were extracted by open-cast methods, though when open-cast methods were not economically feasible, underground workings were employed. A total of five open-cast workings on the Lower Seam, and eight on the Upper Seam, have operated at various times, whilst eleven underground mines have operated at different times, though only one of them was in operation towards the end of mining activities.

GENERAL GEOLOGY

Within the Batu Arang area is found a variety of sedimentary and meta-sedimentary rocks as well as Quaternary sediments (Fig. 2). The Quaternary
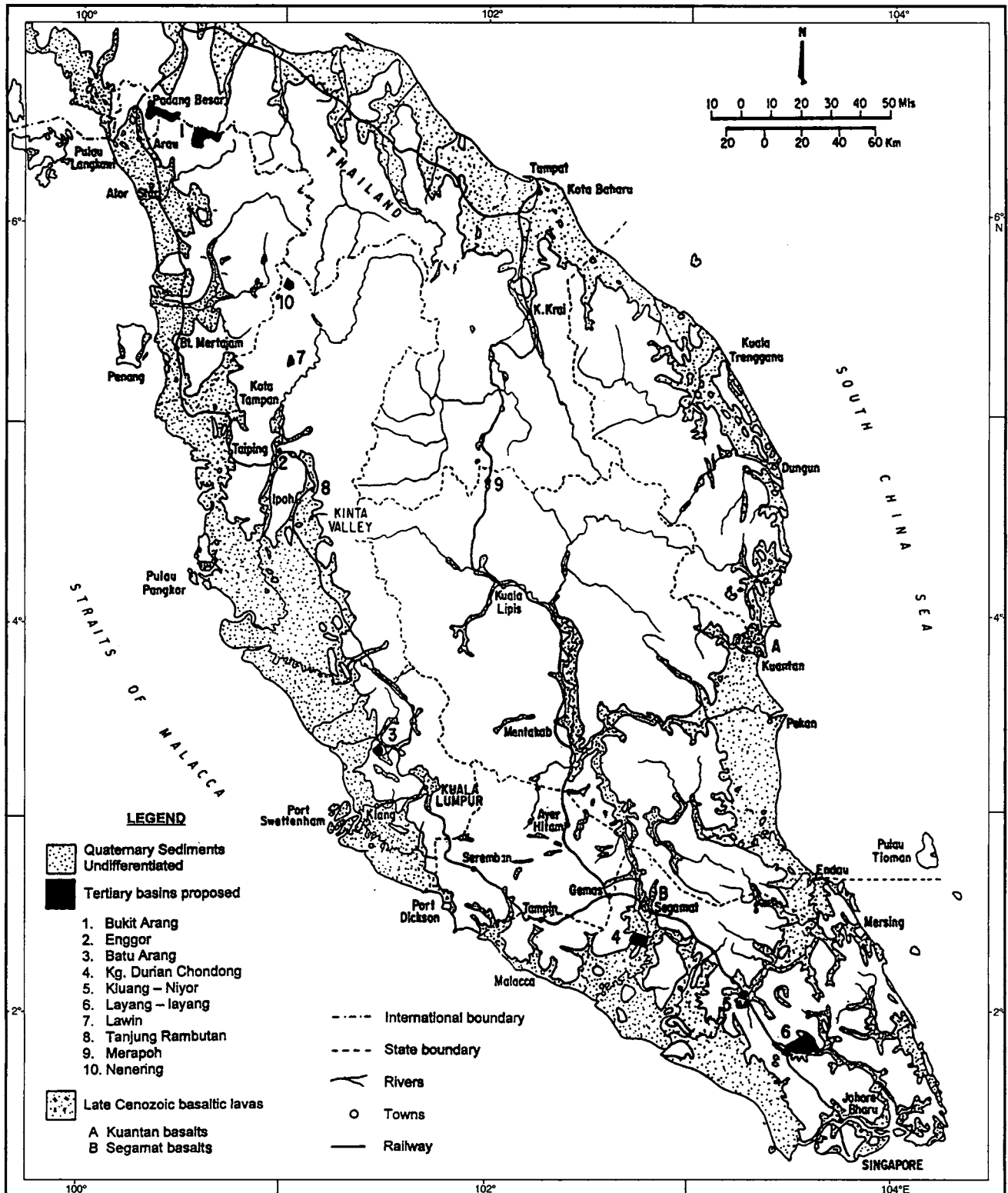
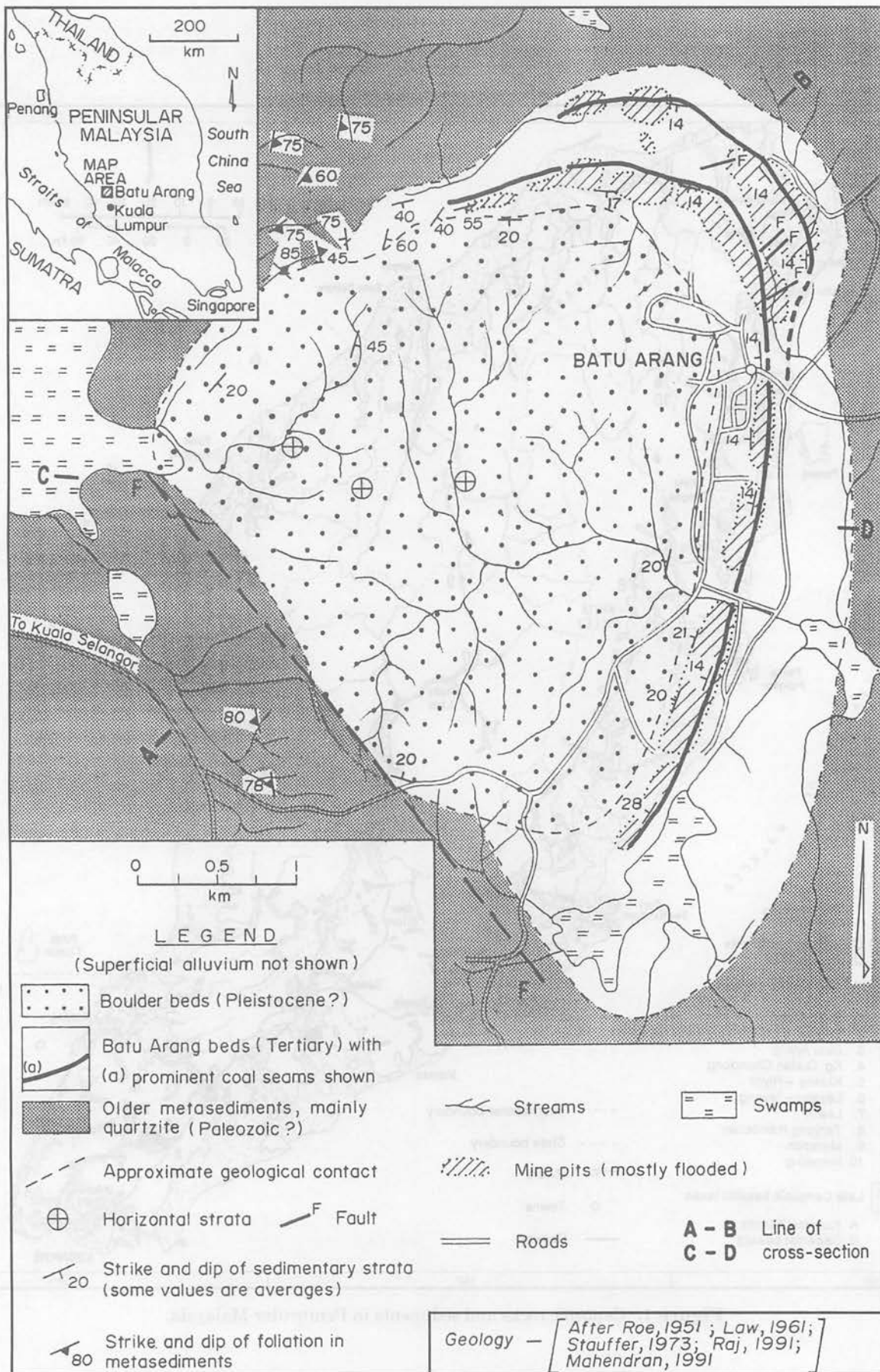**Figure 1.** Cenozoic rocks and sediments in Peninsular Malaysia.

Figure 2. Geological sketch map of the Batu Arang area.

sediments are restricted to the often swampy, flat-bottomed valley floors of the larger, present-day streams and comprise loose, clayey to sandy sediments of a Holocene age. The Tertiary sediments cover about 15 km² and are limited to a trough shaped depression that is approximately elliptical in shape and surrounded by undulating to hilly terrain developed over meta-sedimentary bedrock comprising quartzites, schistose quartzites, phyllites, indurated shales and rare cherts. These meta-sediments also unconformably underlie the Tertiary strata and have been mapped as a part of the Arenaceous Series of a likely Triassic age by Roe (1951). The more recent discovery of crinoid stems and thin shelled bivalves, as well as a few Ammonoid and plant fragments, similar to those from the Kenny Hill Formation (Abdullah Sani, 1985), however, indicates that the meta-sediments are of a Lower to Middle Permian age (Mahendran, 1991).

The meta-sedimentary strata generally strike NNW-SSE with very steep to vertical dips and are moderately to strongly jointed. Thin quartz veins of variable orientations are also commonly found within these strata that are cut by several faults (Law, 1961; Raj, 1991). In the southwest of the area, fault breccia, sheared strata and variations in bedding orientations point to a major NW-SE trending fault that appears to form the southern boundary for the Tertiary basin. No evidence of faulting is, however, seen along the other sides of the basin, though this may be due to weathering and the absence of outcrops in the generally low-lying terrain. Variable bedding strikes and steep dips (> 20°) of the Tertiary strata in the northern part of the basin also suggest the presence of a fault there (Stauffer, 1973). A gravity survey by Mahendran (1991) furthermore, shows the Tertiary strata to be located within a half-graben structure; this basin being delimited to the southwest by the aforesaid NW-SE trending fault.

Field mapping of surface and subsurface bedrock exposures, as well as the interpretation of borehole log, have allowed the Tertiary strata to be separated into two sequences; an upper sequence known as the Boulder Beds which unconformably overlies the lower sequence known as the Coal Measures (or Batu Arang Beds) (Roe, 1951; Stauffer, 1973). The present thickness of the sedimentary fill varies with position in the basin as the eroded top has only relatively small relief, whereas the base of the structure shows marked basinal structure. A maximum thickness in excess of 427 m has furthermore, been proven by a borehole in the central part of the basin (Fig. 3).

BOULDER BEDS

The Boulder Beds form hilly country within the basin and consist of angular to rounded, pebble to boulder sized clasts of mainly quartzite, sandstone and vein quartz and lesser chert, phyllite, schist and shale, fragments, embedded in a sandy to gravelly matrix (Law, 1961; Intan, 1998). The clasts range from 0.07 to 0.7 m in size, though a few are up to 1.7 m in diameter. A few thin beds of sand and sandy clay are also inter-stratified with the gravel beds, whose individual bed thickness can exceed 30 m. The Boulder Beds show variable colours and this, together with differences in the composition and roundness of the clasts, has allowed for differentiation of three inter-fingering sequences (Intan, 1998):

Unit A — The oldest sequence deposited under oxidising conditions and characterized by a reddish colour with subangular to rounded, pebble to boulder sized clasts of mainly sandstone, quartzite, shale, schist, vein quartz and phyllite,

Unit B — The middle sequence with a sulphurous smell and thin pyrite layer, deposited under reducing conditions and characterized by a greyish colour with subangular to angular, pebble to boulder sized clasts of sandstone, quartzite, shale, schist, vein quartz and phyllite, and

Unit C — The youngest sequence deposited under reducing conditions and characterized by a greyish colour with subrounded, pebble to boulder sized clasts of sandstone, quartzite, shale, vein quartz, chert and polymict conglomerate.

The Boulder Beds are horizontal or nearly so in the centre of the basin, though at the edges they show inward dips of 20° to 45°. The beds rest unconformably on the underlying rocks which are Tertiary shales, sandstones and coal, in the east and north of the basin, but Permian quartzites and phyllites in the south and west. In the southwest furthermore, quartzite conglomerates (of Unit A) comprising quartz pebbles in a sandy matrix with abundant secondary iron oxide stains and concretions mark the base of the Boulder beds. The Boulder Beds are more than 300 m thick in the centre of the basin and are cut by several normal faults that are likely to be syn-depositional with throws of only a few feet (Roe, 1951). A number of post-depositional, sinistral wrench faults with displacements of up to 1 m, are also to be seen.
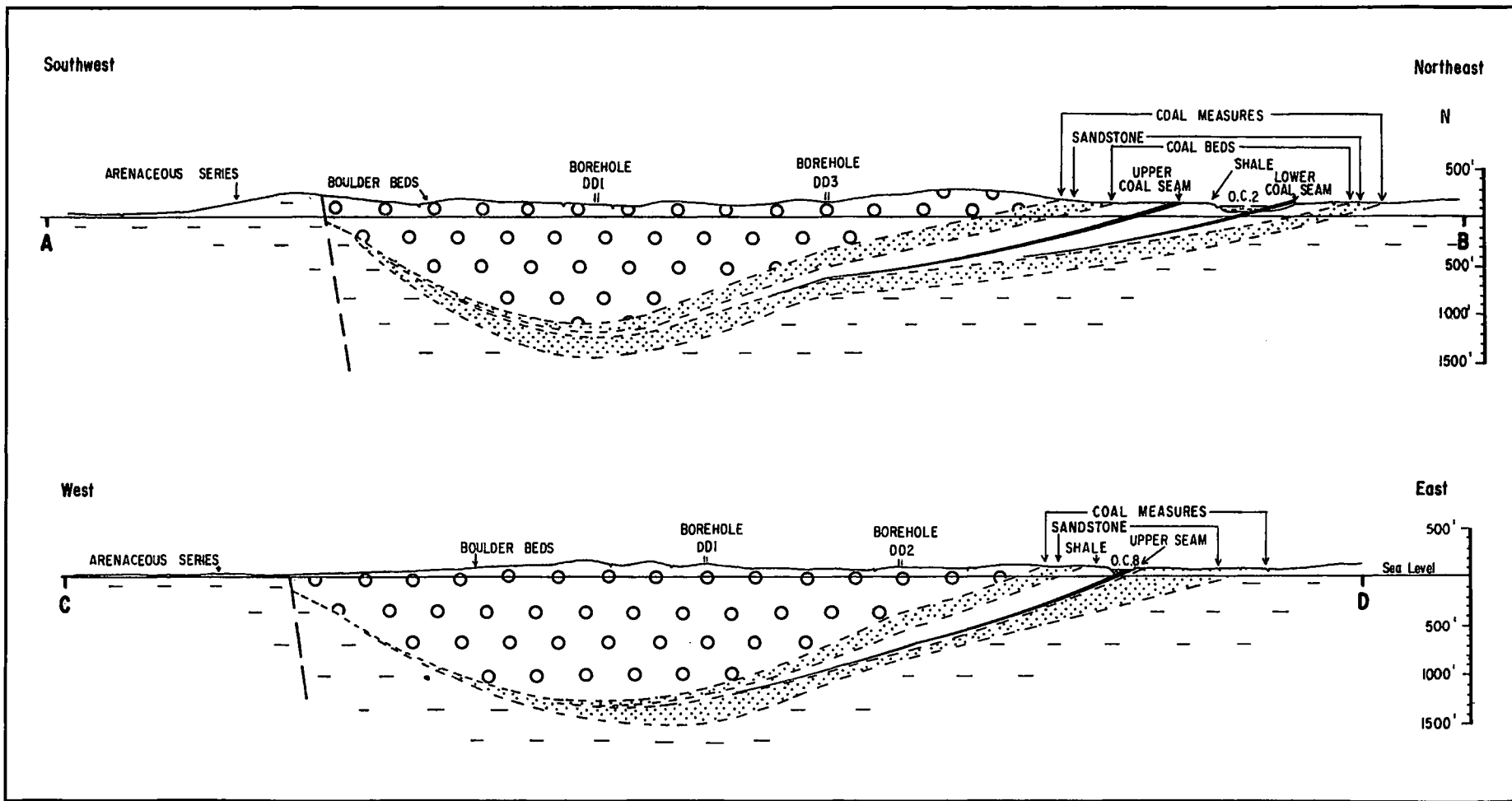
Figure 3. Geological cross-sections in the Batu Arang area (cross-section lines shown in Figure 2).

No fossils have been found within the Boulder Beds that were considered by Roe (1951) to be of a Pleistocene age. The writer, however, considers these Beds to be more likely of a late Middle Miocene to Pliocene age by correlation with regional tectonic events as later discussed.

Sedimentary structures, including pebble imbrications and channel fills, show multi-directional palaeo-current flows, though a general SW to NE flow direction is indicated by an increase in roundness of clasts and a decrease in size (Mahendran, 1991). The clasts have all been derived from nearby areas and deposited by alluvial fans in a seasonal, semi-arid to tropical climate through erosion of steep, fault produced slopes (Stauffer, 1973; Batchelor, 1979). Intan (1998) considers Units A and B to have been deposited by alluvial fans under oxidizing, and reducing, conditions, respectively, whilst Unit C was deposited by debris flows under reducing conditions.

COAL MEASURES (BATU ARANG BEDS)

The Coal Measures (or Batu Arang Beds as termed by Stauffer, 1973) underlie the Boulder Beds and consist of the following facies arranged in the stratigraphical order shown (Roe, 1951):
a) Sandstone, with intercalations of shale and clay;
b) Shale;
c) Coal beds, comprising two main coal seams, shale and sandstone, and
d) Sandstone with intercalations of shale, clay and conglomerate.

The Coal Measures have a maximum recorded thickness of 265 m in the centre of the basin, but along the eastern and northern sides, the sequence is some 183 to 244 m thick. They consist mainly of silty to sandy shales, fine grained sandstones and structureless clay layers as well as thin beds and lenses of coarser grained sandstones and some lignite seams. In the north edge of the basin, a semi-consolidated, poorly sorted, pebbly sandstone comprising angular, pebble sized vein quartz clasts in a fine to medium sand matrix appears to mark the base of the Coal Measures. This sandstone bed, which dips some 25° westwards, is more than 10 m thick and unconformably overlies folded, fine to medium grained sandstones and shales of the Kenny Hill Formation that generally strike E-W with moderate to steep dip angles.

The fine grained sediments range from stiff, structureless clays to well laminated and fissile shales, with colours ranging from light grey through dark grey to brown and black. Carbonaceous matter is abundant in the shales, both in finely disseminated form, and as discrete plant fragments, including some well preserved leaves. The shales are also often silty and even sandy and grade into clayey sandstone in places.

The coal occurs mostly as thin laminae or streaks in dark shales, but also builds thicker layers of more than 30 cm thick. In the eastern part of the basin, two thick coal seams are found as well as some thin beds of coal and coaly shale. The two seams are some 65 m stratigraphically apart; the Upper Seam attaining a thickness of up to 15 m, and the Lower Seam averaging 8 m in thickness. The coal, which appears to be intermediate between high-grade lignite and sub-bituminous coal, is a hard, black rock with a resinous lustre and a tendency towards concoidal fracture. It ranges from dull to shiny and contains laminae of very shiny, hard and brittle, jet-black material. Lenses of clay and sand as well as 'wash-outs' of very fine sand or clay sand are also frequently seen in exposures of the Lower Seam in the northern part of the basin (Law, 1961). The Upper coal Seam has been traced for approximately 5.6 km along strike, whilst the Lower coal Seam extends for almost 2.4 km. The coal seams are, however, not laterally extensive, with the Lower Seam in particular restricted to the northern part of the basin and thinning out southwestwards. The Upper Seam also thins out southwestwards and is not seen in boreholes drilled in the centre of the basin (Fig. 3).

The interbedded sandstones are mostly fine grained, though ranging up to coarse grained, and even pebbly. They show colours of white to various shades of brown depending upon the amount of carbonaceous matter as well as staining by secondary iron hydroxides. Most of the organic matter is in the form of discrete, wavy laminae consisting of mottled, plant fragments and coaly material. Small-scale cross-bedding is very common, with pebbly beds sometimes containing rounded clay pebbles. Clay beds are intercalated with the sandstones which sometimes grade into clayey sandstones. The sandstones consist mainly of subangular quartz grains embedded in a matrix of sericite and chlorite with a few rounded grains of rutile and zircon, while the clayey sandstones consist of very fine, subangular quartz grains in a groundmass of sericite and clay minerals (Law, 1961).

The Coal Measures have yielded thin-shelled, fresh-water gastropods, leaves and leaf impressions which have suggested an Upper Miocene or even Pliocene age. The plant fossils have also indicated that a drier climate, or higher altitude, than present prevailed at the time of deposition of the strata (Scrivenor and Jones, 1919). Pollen analysis has suggested an Late Oligocene to Early Miocene age for the Lower Coal Seam (Mahendran, 1991), but more recent work utilizing palynomorph

assemblages, indicates that the coals are of an Eocene to Oligocene age and deposited in a lacustrine environment under somewhat seasonal climatic conditions (Ahmad, 1993).

Scrivenor (1912 in Renwick and Rishworth, 1966) considered the coal seams to be "drift-formed" ones for they contained most of the evidence for such a coal, i.e. numerous lenticular shale bands suggesting current bedding, the uneveness in the thickness of the seam, the absence of fire-clay and the presence of fine sand immediately below the coal, the high percentage of volatile matter and the presence of a few scattered pebbles of quartzite embedded, at various depths, in the coal. As the coal beds occur in a basin roughly elliptical in shape, Scrivenor (1912) also suggested that they were probably formed in swampy lakes which occupied this depression. Roe (1940) also noted that variations in the beds of the Coal Measures suggested formation in a lake, with disturbed zones in the coal seams representing channels of rivers that drained the swamps where vegetable matter was accumulating. Law (1961) pointed out that thin-shelled, fresh water gastropods, leaves and leaf impressions, as well as filaments of algae and fungi, spores and pollen, together with the mode of occurrence indicated that the coal deposits were of a fresh water origin and probably allochthonous. Renwick and Rishworth (1966) and Mahendran (1991), furthermore, noted that various features, including shale partings and lenses in the coal seams, as well as washouts of fine sand and clayey sand, and angular quartz grains in brown coal suggested formation of the coal seams through accumulation of drifted vegetation in a fresh-water (or perhaps estuarine) environment.

On the basis of organic petrological and geochemical studies, Wan Hasiah (1997) interpreted several sub-environments of deposition within the broad fluvio-lacustrine depositional setting of the Coal Measures. The coal seams were interpreted to be peat-swamp deposits within an alluvial flood plain setting, whilst shales (with TOC < 20%) were interpreted to have been deposited in a freshwater lacustrine setting and carbargillite (TOC 20 to 49%) deposited within smaller ponds or flood basins in the swampy alluvial plain where the peats that formed coals accumulated.

The Coal Measures show a southwestward plunging, synclinal structure, though this has been considered to reflect the basin of deposition, rather then tectonic activity (Roe, 1951). The strata show an average dip of 14° towards the centre of the basin, though local variations are common especially towards the northwest, where the coal seams dip as much as 40° close to the quartzite beds, and in the south where dips of 25° or more are not uncommon

(Law, 1961). In the northwest corner furthermore, the coal seams appear to be bent or folded for their strike shows a sudden change.

Two main joint sets are developed in strata of the Coal Measures; the more prominent one striking 145° and dipping 70° towards 55° with a spacing of 0.2 to 0.7 m, whilst the other is less prominent with similar spacings, but vertical and striking 30°. A third joint set striking 110° and dipping 40° towards 200° is also sometimes found. Joints (cleats) are also present in the coal seams, though their orientations are more variable and their spacings closer, ranging from 0.01 to 0.05 m (Raj, 1995). The main joint set in the coal seams trends N-S with very steep to vertical dips, whilst a minor set trends E-W with similar dips. A third set with similar dips is also present, but strikes 330°. Normal faults, mainly striking 280° to 300° with moderate dip angles and small throws (of up to 1 m) are frequently found, though displacements of as much as 24.4 m have also been reported (Roe, 1951). Reverse faults striking 220° have also been reported at a few places (Mahendran, 1991).

REGIONAL STRATIGRAPHIC CORRELATION

No attempt thus far has been presented on the correlation of the Tertiary strata at Batu Arang with those in neighbouring areas, though such a correlation would provide much data towards unraveling the Tertiary tectonic evolution of Peninsular Malaysia. In view of this, the following review describes the stratigraphy of some known Tertiary basins in neighbouring areas, particularly those in Sumatra, in order to establish a temporal and spatial correlation with the Tertiary strata of Batu Arang.

In the Straits of Malacca (Malaysian waters), the Tertiary basement slopes gently southwestwards with some fifteen grabens having been mapped at discrete locations (Liew, 1994). These grabens, which are elongated in a N-S direction, show maximum depths ranging from 820 m to 3,960 m and mostly have major bounding faults on their western sides. These grabens are believed to have formed during the Lower Oligocene by right lateral wrenching in a NW-SE direction; pre-Tertiary structures having exerted a strong influence on their development. The Tertiary basement topography of some grabens also appears to have been altered by later structural modification during the Miocene with negative flower structures as well as tilting and folding of younger sedimentary sequences. Pleistocene NW-SE striking reverse faults are also superimposed upon the earlier trends (Liew, 1994). No published data, however, is

available on the sedimentary sequences present within these basins.

In Sumatra, on the southwest margin of Sundaland, are found several sub-parallel, approximately N-S aligned, Palaeogene grabens that are separated by basement highs into five groups of basins known (from north to south) as the North, Central, and South Sumatra, Basins, the offshore Southeast Sumatra (Sunda) Basin, and the Northwest Java Basin. These grabens are all now infilled and any remaining surface expression has been largely obscured by recent sediments and/ or recent movements (Moulds, 1989). Of particular significance to the Tertiary Basin at Batu Arang is the large, approximately N-S trending Bengkalis Graben that is located within the Central Sumatra Basin. This graben, when viewed in detail, exhibits a complex structure with the pre-Tertiary basement comprising a series of small, N-S aligned, sub-grabens or basins.

On the northern margin of the Bengkalis Graben, in the Malacca Strait PSC (Production Sharing Contract) area, the Cenozoic sedimentary section has been divided into four depositional/ seismic sequences, each reflecting distinctive stages in the development of the basin (Lee, 1982; Katz and Mertani, 1989; Putrohari, 1992). The oldest sequence, and time-equivalent with the Coal Measures at Batu Arang, is the Permatang Group which was deposited in a humid tropical environment as 'syn-rift' sediments during the late Middle Eocene to Early Oligocene (Robinson, 1987; Longley et al., 1990).

The Permatang Group has been subdivided into four lithostratigraphic units that have been informally assigned formation status, i.e. the Basal Clastics Formation, the Brown Shale Formation, the Mudstone Formation and the topmost Sandstone Formation (Longley et al., 1990). The Basal Clastic Formation of the Permatang Group consists of inter-bedded mudstones and sandstones and is conformably overlain by the Brown Shale Formation which consists of lacustrine mudstones, with some carbonaceous inter-calations, minor siltstones and rare sandstones. These two formations infill a relatively shallow basin formed by gentle basement down-warping and are overlain by the Mudstone Formation, which consists of inter-bedded mudstones and sandstones with rare coals, deposited in a mud-dominated fluvial plain. The areally extensive Sandstone Formation oversteps the underlying formations and consists of sandstones and conglomerates with very thin inter-bedded mudstones, deposited in a broad, sand dominated, fluvial plain (Longley et al., 1990). A phase of mild structural inversion, focussed along the margins of the basin, during the late Early

Oligocene, marked the end of deposition of the Permatang Group and is reflected by a wide spread unconformity. The Permatang Group is blanketed by the Upper Oligocene to Middle Miocene Sihapas Group, which consists of the alluvial to fluvial sandstones with subordinate mudstones of the Menggala Formation, the fluvial sediments of the Transition Formation, the deltaic and shallow marine, sandstones, mudstones and coals of the Sihapas Formation, and the marine shales of the Telissa Formation. These sediments were deposited on a peneplaned post-Permatang surface and record an overall marine transgression, punctuated by minor regressive phases, during a period of relative tectonic quiescence. In the Middle Miocene, after deposition of the Telissa Formation, there was initiated a phase of transpressional tectonism that led to generation of the major structures within the basin and was related to development of the Barisan Volcanic Arc. This compressional tectonic regime had its climax in the Late Miocene to Pliocene, following which the Central Sumatra Basin has been tectonically rather quiet. The third sequence, which records a major regression, is the Middle Miocene to Pliocene Minas Group, which unconformably overlies the older Formations and consists of marine shales of the Petani Formation and deltaic to fluvial sediments of the Lower Minas Formation. The fourth and youngest sequence was deposited during the Quaternary after cessation of tectonism and consists of a veneer of the alluvial-estuarine sands, peats and muds of the Upper Minas Formation (Putrohari, 1992).

On the southeast edge of the Central Sumatra Basin, at the Parum Field, the Cenozoic strata have been separated into seven lithostratigraphic units; the oldest unit being the Lower to Upper Oligocene Kelesa Formation (Heruyono and Villarroel, 1989) that is somewhat time-equivalent with the Coal Measures of Batu Arang. The Kelesa Formation is a graben fill consisting of continental sandstones and conglomerates with tuffaceous shales and contains in places, a lacustrine shale facies with a high organic content. Unconformably overlying the Kelesa Formation along an irregular topographic surface is the Upper Oligocene Lakat Formation, which consists of sandstones derived from Cambro-Ordovician quartzites of the Sundaland craton. Unconformably overlying the Lakat and Kelesa Formations, is the Upper Miocene Tualang Formation which consists of coastal plain and tidal deposits, overlain by lower delta plain deposits, and the Upper Miocene Telisa Formation which consists of calcareous marine shales and siltstones. Increase in volcanism and uplift of the Barisan Mountains during the Middle Miocene led to subsidence and deposition of the Binio Formation

that comprises low-stand fan and delta deposits overlain by highstand marine shales. This was followed by the Upper Miocene Korinci and Plio-Pleistocene Nilo Formations which consist of regressive sands, coals, shales and tuffs. During the Plio-Pleistocene, there was a NE-SW directed compression and this resulted in the present-day structures of the basin with fold axes generally paralleling the underlying NE-SW grain (Heruyono and Villarroel, 1989).

In the Kuala Simpang area of the North Sumatra Basin, Middle Eocene carbonates of the Tampur Formation and arenaceous clastics of the littoral Meucampli Formation, as well as pre-Tertiary low grade metamorphic rocks, dolomite and igneous intrusions, form the economic basement for overlying younger Cenozoic Formations (Sosromihardjo, 1988; Ryacudu et al., 1992). The oldest of these younger Formations, and time-equivalent with the Coal Measures at Batu Arang, is the Late Eocene to Early Oligocene Parapat Formation (also known as the Bruksah Formation) of conglomeratic sands that was deposited as alluvial fans along the Proto-Barisan of the Sumatran Fault System and gradually changed into fluvial plain deposits to the east. These sediments, which rest unconformably over the Tampar Formation or pre-Tertiary rocks, represent the initial infilling of localized NE-SW trending grabens that were completely formed by the end of Early Oligocene. Conformably overlying the Parapat Formation are black shales of the Early to Late Oligocene Bampo Formation that were deposited in a lacustrine/restricted marine environment and completely infilled the NE-SW trending grabens. A continuous transgression in the Early Miocene then led to deposition of the clastic Belumai Formation, whilst to the north, the equivalent basinal facies Peutu Formation limey claystones and shales were deposited. Belumai sedimentation was terminated by deposition of an open neritic carbonate facies in the late Early Miocene. Sedimentation of neritic to bathyal shales of the Lower Baong Formation during the early Middle Miocene followed and reveals maximum trangression in the North Sumatra Basin. Wide spread uplift of adjacent continental margins during this time (early Middle Miocene) then led to deposition of the Lower Baong Sands, while hiatus occurred locally on highs. Uplift of the Barisan mountains, which was initiated in the late Middle Miocene, preceded a period of regression within the Basin that led to deposition of sub-marine fan sediments of the Middle Baong Sands. The Upper Miocene-Pliocene regressive phase commenced with deposition of deltaic sandstones of the Late Miocene Ketupang Formation, followed by deposition of the

continental/parallic Seurula and Julu Rayeu Formations. Unconformably over-lying the Julu Rayeu Formation are Quaternary deposits, consisting of a thin veneer of alluvial gravels, sands and clays, except in the southern part, where the Julu Rayeu Formation was eroded and the Seurula Formation covered by the Quaternary Toba Tuffs (Ryacudu et al., 1992).

In the South Lho Sukon area of the North Sumatra Basin, the younger Cenozoic Formations unconformably overlying the pre-Tertiary and Middle Eocene basement rocks, have been subdivided into six major lithological units; the oldest unit and time equivalent with the Coal Measures at Batu Arang, being the Oligocene Parapat Formation. This Formation, which consists of thin lignite layers, siltstones, claystones and sandstones that sometimes grade laterally into conglomerates, was deposited in fluviatile and parallic environments and represents the initial infilling of localized troughs or grabens in the North Sumatra Basin (Rory, 1990). Early Miocene tectonism led to complete marine withdrawal from the North Sumatra Basin and produced a regional erosional surface above which unconformably lies the Early Miocene Peutu Formation consisting of biogenic reefal build-ups of mainly limestone with dolomite and locally thin shale stringers. After the Early Miocene tectonism, the North Sumatra Basin was tectonically relatively quiet and during the Middle to Late Miocene, rapid subsidence took place resulting in deposition of the very thick marine shales of the Baong Formation that mark the maximum Miocene marine transgression here. A major regressive cycle began during the Late Miocene and continued through Pliocene time, resulting in deposition of the clastic Ketupang, Serula and Julu Rayeu Formations. Thin bedded limestones and lignite are also common in the Juru Rayeu Formation. All of these rocks were mildly folded and faulted during the Barisan orogeny in Plio-Pleistocene time (Rory, 1990). Unconformably overlying all these Formations is Pleistocene to Recent alluvium comprising sand, clay and gravel deposits as well as volcanic tuffs (Rory, 1990).

In the South Palembang sub-basin of the South Sumatra Basin, a major period of tectonism occurred during the Late Cretaceous to Early Tertiary and resulted in a basement configuration of NE-SW to N-S trending horsts and grabens; the pre-Tertiary basement comprising meta-sediments as slate, quartzite and phyllite and granitic rocks (Sarjano and Sardjito, 1989). Within the grabens and unconformably overlying basement, were first deposited in a terrestial environment, the Late Middle Eocene to Early Oligocene Lahat Formation. This Formation, which is time equivalent with the

Coal Measures at Batu Arang, consists mainly of coarse and conglomeratic tuffaceous sandstones in its lower part, but shales (Benakat Shale) in its upper part. During the Late Oligocene to Early Miocene, the Basin started subsiding and there was deposition, in a fluviatile to deltaic environment, of thick sands inter-bedded with thin lignites, shales and siltstones of the lower Grindsand Member of the Talangakar Formation. Conformably overlying this Member is the Transition Member of the same Formation, which consists of shales, clays, sandstones and intercalated thin coal layers, as well as marine shales and calcareous sandstones. After deposition of the Talangakar Formation, the basin broadened to become open sea leading to deposition of the conformably overlying Middle Miocene Baturaja Formation of shallow marine reefal and clastic limestones on basement highs, whilst in other parts, calcareous shales intercalated with sandstones, siltstones, claystones and marls of the Gumai Formation were deposited in a shallow to deep marine environment. In the late Middle Miocene, a regression caused the basin to shallow with the environment becoming neritic and littoral with deposition of claystones intercalated with sandstones and siltstones of the Middle to Upper Miocene Air Benakat Formation. Littoral to terrestial conditions existed in the basin when the late Upper Miocene Muara Enim Formation of claystones intercalated with sandstone, siltstone and coal was deposited. In the Late Pliocene, a basin-wide orogeny occurred and at the same time, the Pliocene Kasai Formation consisting of interbedded tuffs, tuffaceous sandstone and claystone was deposited in fluviatile to terrestial environments. This Plio-Pleistocene orogeny, was dominated by strike-slip movements along NW-SE trending faults and caused all of the basin to be uplifted, folded and faulted into its present form (Sitompul *et al.*, 1992).

From the above review, it is clear that the Coal Measures of Batu Arang (or Batu Arang Beds) were deposited at about the same time as the Parapat Formation in the North Sumatra Basin, the Permatang Group and Kelesa Formation in the Central Sumatra Basin, and the Lahat Formation in the South Sumatra Basin. Similar environmental settings can also be envisaged for all of these Upper Eocene to Lower Oligocene sediments, i.e. flood-plain to lacustrine depositional settings within isolated, fault-bounded basins (grabens or half-grabens). It must, however, be noted that there are some differences in lithology amongst the basins; the differences mainly reflecting local controls on sediment sources and differences in geographic locations. The Sumatran Basins were all located close to the SW coastal margin of Sundaland at relatively low topographic elevations, whilst the Batu Arang basin was located further inland at probably a higher elevation. Such topographic differences are thus reflected in the coal seams of Batu Arang showing evidence of a cooler climate or higher altitude vegetation, and the absence of marine influences, whereas the Sumatran Basins all experienced marine transgressions and regressions after the Early Oligocene.

No lithological equivalent of the Boulder Beds at Batu Arang is seen in the Sumatran Tertiary basins, though it is to be noted that the Beds had to be deposited during an extensional tectonic setting that led to the creation of fault scarps. In view of this, it is here proposed that the Boulder Beds were deposited during, or following, uplift of the Barisan Mountain Range in the late Middle Miocene to Pliocene; the compressional tectonic setting in Sumatra being reciprocated by an extensional tectonic regime in the more inland areas of Sundaland. The Boulder Beds at Batu Arang are therefore, considered to be time-equivalent with the Baong Formation in the North Sumatra Basin, the Minas Group and Binio Formation in the Central Sumatra Basin and the Air Benakat Formation in the South Sumatra Basin.

REGIONAL TECTONIC EVOLUTIONS

The development of the Tertiary strata at Batu Arang and their basinal structure has not been discussed by most workers, though Scrivenor and Jones (1919) suggested deposition in a fault controlled basin. Stauffer (1973) furthermore, pointed out that the rapid lateral wedging of the deposits argued for local downwarping at the time of deposition and that in fact controlled deposition. Stauffer (1973) thus postulated that the basin was produced by Late Tertiary structural adjustments mainly involving faulting. Raj *et al.* (1989) enlarged upon this postulation and considered that left-lateral displacements along two approximately NW-SE trending branches of the Kuala Lumpur fault zone, during the Early Miocene or earlier, led to formation of a pull-apart basin in the Batu Arang area. Deposition of clayey to sandy sediments with abundant organic debris within this basin that was probably bounded to its west by a NNW-SSE trending normal fault, then resulted in the Coal Measures. During deposition, there was continued left-lateral displacements along the two faults and this led to warping of the coal seams close to the NE edge of the Basin.

In view of more recently available published data on the Tertiary basins of Sumatra, a re-evaluation and refinement of the model of Raj *et al.* (1989) is here presented together with reference to

regional tectonics. A brief review of the tectonic histories of the Tertiary Basins of Sumatra is thus warranted in order to develop a model for the tectonic evolution of Batu Arang basin. It is interesting to note here, that the Tertiary grabens and half-grabens that have been mapped at discrete locations within the Strait of Malacca (Malaysian waters) are believed to have to have formed during the Lower Oligocene by right lateral wrenching in a NW-SE direction; pre-Tertiary structures exerting a strong influence on their development (Liew, 1994).

In the Central Sumatra Basin, the pre-Tertiary metamorphic basement, which consists of sutured NW-SE trending terranes, was consolidated by the Jurassic and affected by igneous activity and erosion during the Late Jurassic and Cretaceous (Heruyono and Villarroel, 1989). During the Eocene to Early Oligocene, the basement experienced transtensional stresses which led to formation of N-S trending grabens and half-grabens; the required tectonic setting probably caused by differences in subduction rates along the Sumatra Trench as a result of India colliding with Eurasia (Davies, 1984; Daly et al., 1987). Within the grabens, that developed in response to back-arc extension (Longley et al., 1990), 'syn-rift' alluvial fan, fluvial and lacustrine sediments of the Permatang Group were deposited. A phase of mild structural inversion and erosion, focussed along the margins of the Basin, during the late Early Oligocene, marked the end of deposition and is reflected by a wide spread unconformity (Putrohari, 1992). During the Late Oligocene to early Middle Miocene, Sumatra was tectonically rather quiet; this period being marked by an overall marine transgression punctuated by minor regressive phases. A compressional tectonic regime (transpressional stress) leading to generation of the major structures within the Basin was initiated during the late Middle Miocene and is related to development and uplift of the Barisan Volcanic Arc. This compressional regime had its climax in the Late Pliocene to Pleistocene, following which the Basin has been tectonically quiet.

A somewhat similar tectonic history is also shown by the North Sumatra Basin, whose economic basement consists of pre-Tertiary low grade metamorphic rocks, dolomite and igneous rocks, as well as Middle Eocene carbonates and arenaceous clastics (Ryacudu et al., 1992). During the Late Eocene to Early Oligocene, an extensional tectonic regime was operative in the area leading to formation of NE-SW trending grabens that were infilled with alluvial fan and lacustrine to shallow marine sediments of the Parapat Formation. Altered Triassic granite seen in the basement points to this early Tertiary brecciation. End of deposition

was marked by a phase of mild structural inversion and erosion during the latest Early Oligocene that led to NNW-SSE wrenching (Sosromihardjo, 1988).

In the South Sumatra Basin, a similar tectonic history as that of the North and Central Sumatran Basins is seen, though the basement here mainly consists of Palaeozoic and Mesozoic metamorphics and carbonates that were intensely folded and faulted during the Mesozoic as well as intruded by igneous rocks. Borehole data shows the basement rocks to consist dominantly of quartzites, slates, phyllites and meta-graywackes with occasional limestone and granitoids. The granitoids furthermore, show a distinct distribution pattern, occurring in WNW-ESE trending belts that become successively younger southwards (Pulunggo et al., 1992). During Late Cretaceous to Lower Tertiary times, an extensional stress regime within the area led to the development of NE-SW trending grabens that were bounded by pre-existing N-S and WNW-ESE trending fractures; these fractures having been induced during an Upper Jurassic to Lower Cretaceous compressional tectonic regime. Within the grabens, the Lahat Formation was deposited in a terrestrial environment. During the Late Oligocene to Early Miocene the basin started subsiding and during the upper Middle Miocene a compressive tectonic regime gave rise to inversions. Folding and upthrusting caused by compressive movements became progressively pronounced and reached a peak during Plio-Pleistocene times.

Arising from the above tectonic evolutions, it is considered that Batu Arang was subjected to an extensional tectonic setting during the Late Eocene to Early Oligocene. This extensional setting, which resulted from sinistral displacements along pre-existing approximately NW-SE orientated faults, led to development of a pull-apart basin (of half-graben shape). This extensional tectonic setting, which was also responsible for development of the Sumatran Tertiary Basins, has been interpreted to result from differences in subduction rates along the Sumatra Trench (Davies, 1984; Daly et al., 1987). In the light of more recent published work (Huchon et al., 1994), however, the said extensional tectonic setting is considered to result from the E-W orientated maximum horizontal component of the regional stress field that developed when the Indian Plate collided with the Eurasian Plate at about 50 Ma. Deposition of mainly fine grained sediments, and abundant organic matter, in a swampy, alluvial flood-plain to lacustrine environment within the basin, then led to the strata now represented by the Coal Measures (or Batu Arang Beds). Continued northward movement of the Indian Plate furthermore, led to a progressive clockwise rotation of Peninsular Malaysia, and of

the regional stress field (Huchon *et al.*, 1994), resulting in mild folding and uplift of the Coal Measures during the late Early Oligocene. During the late Middle Miocene, concomitant with, or following, uplift of the Barisan Mountain Range in Sumatra, there developed a extensional tectonic setting in the Batu Arang area which led to uplift of the surrounding areas, and creation of steep scarps, particularly along the pre-existing, NW-SE trending fault boundaries. Rapid erosion of the uplifted areas and scarps then led to development of the Boulder Beds in a subsiding basin with syn-depositional faulting during the Late Miocene to Pliocene. A compressional tectonic setting during the Pliocene, associated with rifting in the Andaman Sea, then led to minor wrench faulting and possibly warping of all the Tertiary strata at Batu Arang. During the Late Pliocene and Quaternary, there was isostatic uplift of the Tertiary strata and basin with subsequent erosion and development of the present-day topography.

It is interesting to note that there are several nearby areas with Quaternary deposits whose northern and southern boundaries appear to be defined in part by NW-SE trending faults, as at Rawang, Ulu Kanching, Kundang, Sungai Buloh, Serendah and Kuala Lumpur. In most of these places furthermore, the Quaternary sediments infill broad, elliptical shaped topographic lows (depressions) that are surrounded by undulating to hilly terrain. In view of the just described tectonic evolution of the Batu Arang Tertiary Basin involving sinistral displacements along NW-SE trending faults, it is therefore, likely that the depressions with Quaternary sediments were also initially developed during pre-Quaternary times, perhaps during the Late Eocene to Early Oligocene.

The presence of Boulder Beds underneath Quaternary deposits in some of the areas, as at Ulu Kanching, supports this suggestion for the Boulder Beds are similar to those at Batu Arang (Stauffer, 1973). There are, however, differences in the type of basement bedrock, for the basin at Batu Arang is developed over clastic meta-sedimentary rocks, whereas the basement bedrock of most of the other areas is limestone or marble. It can therefore, be speculated that basement lithology also influenced the development of pull-apart basins.

The Sungai Buloh area furthermore, is located within a zone that is demarcated by the two NW-SE trending faults along which sinistral displacements are assumed to have occurred during the Late Eocene to Early Oligocene. In view of a likely granitic and/or meta-sedimentary bedrock under the Quaternary deposits, it is predicted that there is likely to be a Tertiary Basin in the Sungai Buloh area; this basin developing along the same lines as the one at Batu Arang.

CONCLUSION

It is concluded that the Coal Measures (or Batu Arang Beds) at Batu Arang are time-equivalent (Late Eocene-Early Oligocene) with, and have a similar depositional history as, the Parapat Formation of the North Sumatra Basin, the Permatang Group and Kelesa Formation of the Central Sumatra Basin, and the Lahat Formation of the South Sumatra Basin. Differences in lithology reflect differences in geographical locations; the sediments at Batu Arang having been deposited at higher altitudes in a more inland area. The Boulder Beds at Batu Arang are considered to be time-equivalent (Middle Miocene-Pliocene) with the Baong Formation of the North Sumatra Basin, the Minas Group and Binio Formation of the Central Sumatra Basin, and the Air Benakat Formation of the South Sumatra Basin.

It is also concluded that a pull-apart basin (of half-graben shape) developed at Batu Arang during the Late Eocene to Early Oligocene as a result of sinistral displacements along two pre-existing, NW-SE trending faults. Deposition in a swampy, alluvial flood-plain to lacustrine environment within the basin, then led to the strata now represented by the Coal Measures (or Batu Arang Beds). During the late Early Oligocene, a rotation of the regional stress field led to mild folding and uplift of the Coal Measures which subsequently experienced erosion. During the late Middle Miocene, concomitant with, or following, uplift of the Barisan Range in Sumatra, there occurred uplift of the areas surrounding Batu Arang, and the creation of steep scarps whose rapid erosion led to development of the Boulder Beds in a subsiding basin with syn-depositional faulting during the Late Miocene to Pliocene. Minor wrench faulting in the Pliocene was followed by isostatic uplift of the Tertiary strata with subsequent erosion during the Late Pliocene and Quaternary.

ACKNOWLEDGEMENTS

REFERENCES

ABDULLAH SANI B. HASHIM, 1985. Discovery of an Ammonoid in the Kenny Hill Formation and its significance. *Newsletter, Geol. Soc. Malaysia, 11(5)*, 205-211.

AHMAD, M.K., 1993. Tertiary palynomorphs from Batu Arang, Malaysia (Abstract). *Newsletter, Geol. Soc. Malaysia, 19(3)*, 116.

BATCHELOR, B., 1979. Geological characteristics of certain coastal and offshore placers as essential guides for tin exploration in Sundaland, Southeast Asia. *Bull. Geol.*

Soc. Malaysia, 11, 283-313.

DALY, M.C., HOOPER, B.G.D. AND SMITH, D.G., 1987. Tertiary plate tectonics and basin evolution in Indonesia. *Proc. 16th Ann. Conv., Indonesian Petroleum Assoc., 1,* 399-428.

DAVIES, P.R., 1984. Tertiary structural evolution and related hydrocarbon occurrences, North Sumatra Basin. *Proc. 13th Ann. Conv., Indonesian Petroleum Assoc., 1,* 19-49.

HERUYONO, B. AND VILLARROEL, T., 1989. The Parum Field: An example of a stratigraphic trap in P.T. Stanvac's Central Sumatra Kampar Block. *Proc. 18th Ann. Conv., Indonesian Petroleum Assoc., 1,* 193-216.

HUCHON, P., LE PICHON, X. AND RANGIN, C., 1994. Indochina Peninsula and the collision of India and Eurasia. *Geology, 22,* 27-30.

INTAN SUHAILA BT. MUSTAFA, 1998. *Sedimentologi dan stratigrafi Lapisan Boulder, Kawasan Batu Arang, Selangor.* (Unpubl.) B.Sc. (Hons) Proj. Report, *Univ. Malaya,* 32p.

KATZ, B.J. AND MERTANI, B., 1989. Central Sumatra — A geochemical paradox. *Proc. 18th Ann. Conv., Indonesian Petroleum Assoc., 1,* 403- 425.

LAW, W.M., 1961. *The Batu Arang Coalfield, Selangor.* (Unpubl.) B.Sc. (Spec) Thesis, Univ. Malaya, 56p.

LEE, R.A., 1982. Petroleum geology of the Malacca Strait Contract area (Central Sumatra Basin). *Proc. 11th Ann. Conv., Indonesian Petroleum Assoc.,* 243-263.

LIEW, K.K., 1994. Structural patterns within the Tertiary basement of the Strait of Malacca (Abstract). *Newsletter, Geol. Soc. Malaysia. 20(3),* 233-234.

LONGLEY, I.M., BARRACLOUGH, R., BRIDDEN, M.A. AND S. BROWN, 1990. Permatang lacustrine petroleum source rocks from the Malacca Strait PSC, Central Sumatra, Indonesia. *Proc. 19th Ann. Conv., Indonesian Petroleum Assoc., 1,* 279-297.

MACKIE, J.B., 1938. Malayan Collieries Limited, Batu Arang. *Supp. Ann. Rept. For 1937, Chief Inspector of Mines, Fed. Malay States,* 59-74.

MAHENDRAN, G., 1991. *The geology of Batu Arang, Selangor Darul Ehsan.* (Unpubl) B.Sc. (Hons) Thesis, Dept. of Geol., *Univ. Malaya,* 140p.

MOULDS, P.J., 1989. Development of the Bengkalis Depression, Central Sumatra and its subsequent deformation — A model for other Sumatran grabens?. *Proc. 18th Ann. Conv., Indonesian Petroleum Assoc., 1,* 217-245.

POWELL DUFFRYN TECHNICAL SERVICES LTD., 1954. *Report On Malayan Collieries Ltd.,* 49p.

PULUNGGONO, A., AGUS, H.S. AND KOSUMA, C.G., 1992. Pre-Tertiary and Tertiary fault systems as a framework of the South Sumatra Basin; A study of SAR-maps. *Proc. 21st Ann. Conv., Indonesian Petroleum Assoc., 1,* 339-360.

PUTROHARI, R.D., 1992. MSDC-1: A gas discovery well in the Malacca Strait PSC, Sumatra, Indonesia. *Proc. 21st. Ann. Conv., Indonesian Petroleum Assoc., 1,* 201-223.

RAJ, J.K., IDRIS B. MOHAMED, SIVAM, S.P. AND S. PARAMANANTHAN,

1989. The Bilut Valley of Pahang State and the Cenozoic of Peninsular Malaysia (Abstract). *Newsletter, Geol. Soc. Malaysia, 15(1),* 34.

RAJ, J.K., 1991. Anticipated subsidence in the Batu Arang area, Negeri Selangor Darul Ehsan. *(Unpubl. Rept.),* 25p., 2 Maps, 2 Figs. [Confidental].

RAJ, J.K., 1995. Point load strengths of Tertiary sedimentary rocks from the Batu Arang area, Peninsular Malaysia. *Malaysian Jour. Science, 16B(1),* 49-57.

RENWICK, A. AND RISHWORTH, D.E.H., 1966. *Fuel Resources (Coal, Lignite and Petroleum) in Malaya.* Geol. Survey Dept., West Malaysia, Ipoh, 123p.

ROBINSON, K.M., 1987. An overview of source rocks and oils in Indonesia. *Proc. 16th Ann. Conv., Indonesian Petroleum Assoc., 1,* 97-122.

ROE, F.W., 1940. The coal field at Batu Arang, Selangor. *1940 Yearbook, Fed. Malay States Chamber of Mines,* 142-150.

ROE, F.W., 1951. The Geology And Mineral Resources of The Neighbourhood of Kuala Selangor And Rasa, Selangor, Federation of Malaya, With An Account of The Geology of The Batu Arang Coal-Field. *Geo. Surv. Dept., Fed. Malaya, Mem. 7,* New Series, 163p.

RORY, R., 1990. Geology of the South Lho Sukon 'A' Field, North Sumatra, Indonesia. *Proc. 19th Ann. Conv., Indonesian Petroleum Assoc., 1,* 1-30.

RYACUDU, R., DJAAFAR, R. AND GUTOMO, A., 1992. Wrench faulting and its implication for hydrocarbon accumulation in the Kuala Simpang area — North Sumatra Basin. *Proc. 21st Ann. Conv., Indonesian Petroleum Assoc., 1,* 1-30.

SARJONO, S. AND SARDJITO, 1989. Hydrocarbon source rock identification in the South Palembang sub-basin. *Proc. 18th Ann. Conv., Indonesian Petroleum Assoc., 1,* 427-453.

SCRIVENOR, J.B. AND JONES, W.R., 1919. *The Geology of South Perak, North Selangor And The Dindings.* Government Press, Kuala Lumpur, 196p.

SITOMPUL, N., RUDIYANTO, WIRAWAN, A. AND Y. ZAIM, 1992. Effects of sea level drops during late Early Miocene to the reservoirs in South Palembang sub basin, South Sumatra, Indonesia. *Proc. 21st Ann. Conv., Indonesian Petroleum Assoc., 1,* 309-324.

SOSROMIHARDJO, S.P.C., 1988. Structural analysis of the North Sumatra basin — with emphasis on synthetic aperture radar data. *Proc. 17th Ann. Conv., Indonesian Petroleum Assoc., 1,* 187-209.

STAUFFER, P.H., 1973. Cenozoic. Chp. 6. *In:* Gobbett, D.J. and Hutchison, C.S. (Eds.), *Geology Of The Malay Peninsula.* Wiley-Interscience, U.S.A., 143-176.

WAN HASIAH ABDULLAH, 1997. Depositional palaeoenvironment determination based on organic facies characterisation — a case study of the Batu Arang coal-bearing sequence, (Abst.). *Summary of Abstracts, Ann. Conf. 1997, Geol. Soc. Malaysia,* 93.